These tubes have now been tried on several occasions, with entire success. If I am at all doubtful about bleeding, I introduce one of them, and retain it for twenty-four hours or so, according to circumstances. Since I have used them, I have had no fear or trouble in dealing with primary or secondary hæmorrhage, either in lithotomy or in some of the deep sections of the prostate or prostatic bars I have made. It has, in fact, proved a most reliable plan of exercising digital compression on bleeding vessels, which cannot be tied, and where styptics of all kinds are undesirable. These tubes can be readily removed; thus the wound is kept clean and free from the collection of septic influences. Though the size of these tubes may be taken as representing considerable openings into the bladder, I do not think exception can be taken to them on these grounds. When the proper time arrives for closing a bladder, which, in its construction, provides cause for the production of stone, for the maintenance of cystitis, and the symptoms that one or other of these, conjointly or independently, produce; when urine escapes from the open bladder with an acid, and not a fœtid alkaline reaction, then it will be found that a large opening heals quite as quickly, and much more soundly relatively to the parts above it, than a small one.

AN EXPERIMENTAL AND CLINICAL STUDY OF AIR-EMBOLISM.[1]

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SUDDEN and unexpected death during an operation is a calamity which never fails to strike terror to the heart of the boldest surgeon. Although death is a frequent and familiar visitor wherever human beings exist, nevertheless its sudden and unforeseen advent conveys with it more than the usual halo of sadness, and when such a scene transpires in the operating room it leaves impressions which neither time nor space can erase. Disasters of this kind come without warning, and usually at a time when least expected. The surgeon who has the misfortune to meet with such an accident is not only destined to burden his memory with the unpleasant remembrances of the incident for the remainder of his days, but in addition he is often made an unjust object of reproach by those who are unable to appreciate the nature of the case. His conscience may be relieved by a favorable verdict regarding his conduct and management of the case before the only competent tribunal, composed of his colleagues and the medical press, but that most uncertain of all things, public opinion, will in all probability be arrayed against him. In one sad moment the object of his ambition, the ultimate aim of his life-work has suffered irreparable loss. The surgeon who seeks to maintain and advance the interests of his profession as well as his own reputation should familiarize himself with all the causes and conditions which may precipitate such an unhappy result, with a view to adopt and apply timely prophylactic measures. Believing that it is good practice to prepare for war in time of peace, I intend on this occasion to call your attention to one of the most dreaded and, I may add, one of the most uncontrollable causes of sudden death—I allude to air-embolism.

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After consideration of the subject from an historical, experimental and clinical standpoint, I shall endeavor to point out the conditions remote and direct which give rise to this accident. The different explanations of the immediate cause of death will be discussed, and, finally, I shall offer some practical suggestions relating to the prophylactic and therapeutic measures.

By air-embolism I understand the presence of free atmospheric air within the vascular system during life, and in sufficient quantity to give rise to symptoms of obstruction. It is a true embolism inasmuch as the location of the volume of air which constitutes the embolus is always some distance from its point of entrance. The presence of air in a vessel offers the same mechanical obstruction to the flow of blood as a solid substance, and gives rise to the same disturbance of circulation in the tissues supplied by the vessel. An air-embolus differs from an ordinary embolus in that when once introduced into the circulation it is capable of being broken up or divided by the blood current and the action of the heart, and on this account usually becomes the source of multiple emboli. Pathologically it always differs from a solid embolus, inasmuch as it is more likely to be removed by absorption and is less liable to be followed by thrombosis. Air-embolism is always due to the introduction of atmospheric air into a wounded or injured vein, and, in contradiction to the ordinary form of embolism, it is primarily most always found in the right side of the heart and in the venous system. With a view to study the immediate effects of the presence of a considerable amount of air on the heart and the vessels, it becomes necessary to allude to the experiments which have been made where embolism was artificially produced by the introduction of solid substances into the circulation.

I. ON THE IMMEDIATE CAUSE OF DEATH BY RAPIDLY FATAL EMBOLISM.

The most interesting experiments on embolism were made by Virchow in 1847 and by Panum in 1854–1855, and although the conclusions of these experimenters are somewhat at variance, our present knowledge on this subject is based upon the conjoined labors of these distinguished writers.

Virchow was convinced that his experiments were conclusive in showing that complete embolism of the pulmonary artery would prove invariably fatal in a short time, while partial obliteration of this vessel produces either no symptoms at all or only temporary dyspnœa, restlessness and a sense of oppression. He gives the following explanation to account for the immediate cause of death in cases of complete obstruction in the pulmonary artery by a large embolus. (Gesammelte Abhandlungen, p. 297.) "The first effect of the pulmonary ischæmia is the interruption of the supply of oxygenated blood to the coronary arteries of the heart and the arteries of the body, as well as the stasis of the venous blood in the right side of the heart, the coronary veins and the veins throughout the body. These conditions result in the arrest of the heart's action in the diastole, the tetanic contractions of the voluntary muscles, the retardation of respiration, the dilatation of the pupils, the protrusion of the eyeballs, etc., and very soon complete death."

Panum, by a series of very ingenious experiments, disproved the assertions of Virchow, that a lack of arterial blood in the coronary arteries produces instantaneous arrest of the heart's action. (Experimentelle Beiträge zur Lehre der Embolie, Virchow's Archiv., Vol. XXV., p. 308.) In a rabbit, where the ventricular contractions had ceased for fully fifteen minutes, and where only the right auricle continued to pulsate, he injected a warm black mass, composed of tallow, wax and soot, into the aorta, for the purpose of studying more accurately the anatomical relations of the coronary arteries. The injection penetrated the smallest vessels. The right auricle continued its rhythmical movements for three and a half hours after the injection was made,—the heart and lungs having been removed from the body. In the second experiment he divided both pneumogastric nerves in a dog, and then opened the chest and pericardium and passed a double ligature underneath the innominate artery; after tying the upper ligature and drawing the lower tight, the artery was opened between them, and a silver tube introduced and secured in the vessel with a proximal ligature. The silver tube was connected with a glass tube by interposing a piece of rubber-tubing. To the distal end of the glass tube another piece of rubber was attached, and all tubes filled with oil, which was kept from leaving the tube by a clamp. The aorta was compressed with a spring forceps above the origin of the innominate artery, and the same black mass was injected throught the tube into the aorta. The oil and black mass entered the vessel, and, after closing the aortic valves, filled the coronary arteries, which were found completely blocked with the foreign substance. The movements of the heart were carefully observed before, during, and after the injection was made. Before the injection the contractions were regular, 80-90 per minute during the injection, on account of the higher temperature of the injection (45° C.), the contractions became more rapid, and in the left side of the heart, which was distended with blood, they were less forcible, an occurrence which could readily be accounted for by the mechanical obstruction to the outflow from the left ventricle. All the chambers of the heart continued to contract for five minutes after the injection was complete. Six minutes after the injection was made the contractions of the left auricle ceased. The movements of the ventricles were feeble, but could be plainly seen. The rhythm of the ventricular contractions grew slower than the contractions of the right auricle, and, at the same time were less regular. After 25 minutes the right auricle pulsated 48, the ventricles 24 times per minute. Five minutes later the pulsations of the auricles and ventricles were the same in frequency. Forty minutes after the injection the ventricles contracted 24 times per minute to eight auricular pulsations. Fifty minutes after the injection the ventricles made 23 rhythmical movements to three of the auricles. After one hour the movements of the heart again became regular, inasmuch as the auricle and ventricles pulsated 13 times per minute, and in such a manner that the movements of the ventricles followed immediately after the contraction of the auricle, and were followed by a long diastolic pulse. Seventy-five minutes after the injection the movements of the left ventricle ceased, while the right half of the heart contracted regularly eight times per minute. Two minutes later the ventricle contracted only twice to eight movements of the auricle. Ninety minutes after the injection the right ventricle ceased to beat, while the right auricle continued to contract for six hours and ten minutes after the injection, making toward the last only one movement per minute. After all pulsations had ceased for a while, they were renewed by blowing upon the heart. These contractions continued for seven and one-half hours after the injection, and even after they had ceased for a second time, they were again excited by mechanical irritation. During this observation the heart was kept at a temperature of 12.5 to 13° C., under a glass bell in which the air was saturated with moisture. An examination of the heart showed that the coronary arteries were completely distended with the black mass, and that capillary vessels and coronary veins were blocked with oil. A few drops of oil, but nothing of the black mass were found in the right auricle. The aorta, near the heart, was filled with the injection material; the aortic valves were so completely closed that nothing had penetrated into the ventricle. In two other instances the coronary veins were made impermeable in a similar manner, and the contractions of the heart were temporarily arrested by electric irritation of the pneumogastric nerves. This experiment was repeated in both animals more than twenty times, and always with the same uniform results. If the electric stimulation was continued, after the heart had ceased to contract, the movements were again excited, but this always required a continuation of the current for at least a minute. If the electrodes were removed after the heart ceased to act, it required twenty seconds before the contractions were re-established, the movements being always more rapid than before the irritation was applied. From these experiments, we are forced to conclude that embolism of the coronary arteries is insufficient to produce instantaneous arrest of the heart's action. Virchow quotes Erichsen as having observed prompt cessation of the movements of the heart after ligation of the coronary arteries, but Panum doubts the possibility of performing this operation upon the heart of a living animal.

The same observer studied embolism of the pulmonary artery by injecting an emulsion of gum arabic, in which were suspended small pellets of black wax, into the jugular vein of a medium sized dog. Eight c.ctm. of the emulsion were injected. All signs of life and all reflex movements ceased three minutes after the injection. After death the large vessels were tied, in order to ascertain the exact quantity of blood contained in each side of the heart. The right side contained 112.35 grms. of dark-colored blood; the left contained only 6.45 grms. In another experiment he injected coarsely powdered charcoal in suspension into the jugular vein of a dog. The time which elapsed between the injection and cessation of life was longer than in the preceding case, consequently the left side of the heart contained a larger amount of blood, although the quantity was small when compared with that of the right side of the heart. In all cases of death resulting from embolism of the pulmonary artery, the amount of blood found in the left side of the heart is proportionate to the completeness of the obstruction in the pulmonary artery. The left side of the heart is never found completely empty, as the labored respiratory movements will force the blood which is present in the pulmonary vein and its branches into the left side of the heart. If, instead of using small emboli, large plugs are injected, as was done by Virchow, the blood contained on the distal side of the obstruction will pass through the pulmonary circulation and reach the left side of the heart; consequently, in such cases more blood will be found in the left ventricle. Panum asserts also, that the cessation of the heart's action does not invariably take place so early that it can be considered as the primary and direct cause of death. As a rule he found the heart pulsating after the death-struggle had been initiated, from arrest of innervation from the cerebro-spinal centre. In some instances the heart continued to pulsate after all signs of animal life emanating from the brain and spinal cord had ceased. Shortly after respiration was arrested, the heart did cease to pulsate, and, as Virchow has stated, in the diastole.

According to Panum, the cessation or continuation of the heart's action exerts no influence for good or evil in cases of extensive embolism. He claims that if the cessation of the heart's action takes place as one of the first effects after embolism of the pulmonary artery, as was noted in Virchow's first case, it must be regarded, under certain circumstances, as being the result of irritation of the pneumo-gastric nerves, so much more so, as the heart, in the case referred to, again began to pulsate after the thorax was opened. As a rule the heart's action is arrested by distension of the right ventricle.

Other observations tend to show that the distension of the right ventricle is the cause. The excess of carbonic acid gas and the diminished supply of oxygen must also be taken into account. Other experiments have demonstrated that carbonic acid in concentrated form, injected into the heart after its re moval from the chest, readily leads to diastolic paralysis, and that the organ commences to beat again when exposed to air. The arrest of the heart's action is due to mechanical dilatation and the presence of an excess of carbonic acid. The first and most constant symptom resulting from sudden and extensive embolism is a high degree of anæmia in all visible parts of the body. On post-mortem examination the white substance of the brain is completely bloodless, especially if small and numerous emboli have been injected. This general anæmia is followed by tetanic stretching of all extremities, involuntary discharges and deep convulsive inspiratory movements. Ligature of both carotid arteries does not produce such an intense ischæmia of the brain. If the vertebral arteries are ligated at the same time, the tightening of the ligature of the second vertebral artery produces syncope and convulsions, but the symptoms are less intense than after sudden fatal embolism of the pulmonary artery. Panum also induced cerebral anæmia by injecting black pellets of wax, suspended in an emulsion, into the crural artery of a dog, throwing the injection in a central direction through a catheter which had been passed into the artery near the heart, producing thus multiple embolism in all of the smaller arteries. The animal lost only a few drops of blood, and no air entered. The animal was taken immediately with tetanic convulsions, involuntary discharges, and all organs accessible to the eye presented an extremely anæmic appearance. All reflex symptoms were arrested after one or two minutes. Two other experiments were followed by the same results. In all cases the small wax pellets were found in large numbers in the small vessels of the brain, as well as in all other parts of the body. In four other dogs cerebral embolism was avoided by introducing the catheter only as high as the ribs, and by injecting slowly. During the injection, a peculiar tremor was observed which affected the muscles of the lower extremities, which, however, soon ceased, and gave way to comple paralysis of both motion and sensation, as well as complete arrest of all reflex movements. One of the animals survived the experiment 22 hours, the second nine and one-half hours, the third six hours, and the fourth five hours. The small vessels of the spinal cord were found obstructed by the small wax pellets; the vessels between the emboli and the heart were much dilated, and showed many small extravasations. The spinal cord was the seat of red softening, which was more conspicuous the longer the life of the animal was prolonged. The spinal cord above the middle of the dorsal region, and the brain, were normal in appearance, although scattering pellets were found here also. It will be seen that Panum, in contradistinction to Virchow, attributes the immediate cause of death, in cases of rapidly fatal embolism, to acute cerebral anæmia. From a study of the literature on air embolism, it is evident that the immediate cause of death has been assigned by different pathologists to one of the following conditions:

1. Mechanical dilatation of the heart and paralysis of the organ in the diastole.
2. Acute cerebral ischæmia.
3. Asphyxia resulting from mechanical obstruction to the passage of the blood through the pulmonary circulation.

As we shall see further on, death from air embolism is not always produced in the same manner; the mode of dying varies, and is modified by:

1. The amount of air admitted.
2. The time which has elapsed between the ingress of air and the fatal issue.
3. The location and distribution of the emboli.

II. HISTORY OF AIR-EMBOLISM.

Surgeons and pathologists have for a long time been aware of the deleterious effects of free atmospheric air in the vascular system. The danger attending the forcible insufflation of air into the veins of animals was well known to many of the earlier physiologists. Among the first to study the effects of the introduction of air into veins may be mentioned Redi, Wepfer, Camerarius, de Heyde, Harder, Bohnius, Boerhave, Lancisi, Morgagni, Valsalva, Bichât and Nysten.

As early as 1667, Redi killed animals by intra-venous injections of air. He observed during his experiments that the pulse became intermittent, an occurrence which he attributed to the passage of a large air bubble through the heart. His followers, who repeated the experiments, soon discovered that after forcible insufflation of air into veins the air became diffused, inasmuch as at the post-mortem examinations they found it present in the right auricle, the coronary vessels, and, in the shape of air bubbles, in the smaller vessels. Mery made the observation that in opening the abdomen of a dog and puncturing the vena cava above the origin of the emulgents, as the vein became emptied of blood, it filled with air which ascended with the blood current and entered the right side of the heart. Haller witnessed the same phenomenon in cold blooded animals after wounding some of the large venous trunks. He has shown that it was from this source that the air was derived, which Redi, Caldesi and Morgagni had seen circulating in the vessels of the same animals. He claimed that air is never seen in vessels when the necessary precautions are exercised to prevent its introduction through a wounded vein. Nysten found that by injecting air slowly into a vein, so as not to produce death of the animal, that the coloring of the arterial blood was rendered imperfect. He satisfied himself that this change was not owing to the embarrassment of respiration. Insufflation of oxygen had no effect in preventing or correcting this change of color in the arterial blood. The literature on insufflation of air into veins is quite prolific, and the subject cannot be justly dismissed without an allusion to the following names: Blochmann (*Aër in venis causa mortis*, Dresden, 1843); Bouillaud (*De l' introduction de l'air dans les veines*, Paris, 1838); Gain (*de aëris ingressione in venas*, Berlin, 1865); Maguin (*Etude expérimentale sur l'introduction forcé et sur l'entrée spontanée de l'air dans les veines*, Nancy, 1879); Méric (*Recherches sur l' introduction de l' air et des gaz qui le constituent dans le système veineux*, Paris, 1866); Valkenhoff (*De aëris in venas ingressu ejusque effectu lethali*, 1840), and Laborde (*Effects de l' introduction de l'air dans la circulation artérielle*, Compt. rend. Soc. de biolog., Paris, 1873), names which are intimately associated with the experimental part of the history of air-embolism.

It was not long after the deleterious effects of free atmospheric air in the veins of animals had been studied experimentally before the same symptoms were observed in man by the accidental admission of air into wounded veins during operations, and in some of the first cases the presence of air in the veins and right side of the heart was demonstrated by post-mortem examinations. Although a number of honest and reliable surgeons, prominent among them Velpeau and Fergusson (*Lettre sur l' introduction de l'air dans les veines de l'homme*, Gaz. méd., Paris 1838, pp. 113–121), have denied that a sufficient amount of air can be admitted through a wounded vein to produce sudden death, this assertion is no longer tenable in the face of such a large number of well authenticated cases as have been recorded in surgical literature by equally conscientious and competent observers. Since the publication of the first well authenticated case observed by Beauchêne and described by Magendie, the following authorities, placed in alphabetical order, have reported similar cases:

Assmus, *Zur Casuistik des Lufteindringens in grössere Venenstämme*, Med. Zeitung, Berlin, 1842, XI., p. 104; Amussat, *Introduction de l'air dans les veines*. Bulletin Acad. de Méd., Paris, 1836, I., pp. 894–899 (1837–38); II., p. 363, 461; Barlow, An attempt to remove a tumor on the neck, entrance of air in vein, sudden death, Med. Chir. Trans. (1830), XVI., pp. 28–35; Chassaniol, *Observation de l'entrée de l'air dans les veines pendant l'amputation du bras, dans son articulation scapulo-humérale*, Union méd., Paris, 1869, VIII., p. 428; Clémot, Lanc. franc., 1830, Tom. I., p. 357; Coolidge, Case of sudden death from entrance of air into the jugular vein, *N. Y. Med. Gazette* (1841–2), I., p. 305; also *N. Y. Med. Journal* (1847), Vol. IX., pp. 199–201; B. Cooper, Case of alarming syncope from the admission of air into a vein during amputation of the shoulder joint, *London Lancet* (1843), Vol. I., pp. 448–451; Cormack, Case of death from the entrance of air by a rigid vein in the neck, opened accidentally by a seton-needle, *London Medical Journal* (1850); Delaporte, *Extirpation d'une tumeur situeé au cou; introduction de l'air dans le système vasculaire*, Bulletin Acad. de méd., Paris (1837), I., p. 132; Delpech, Mém. des hospitaux du midi. (1830), No. 16, p. 231; Fischer, H., *Ueber die Gefahren des Lufteintritts in die Venen während einer Operation*, Volkmann's Sammlung Klin. Vortræge, Chirurgie No. 34; Gunn, Syncope from entrance of air into the facial vein, *New York Medical Journal* (1852), p. 356; Heckford, Four cases of entry of air into the circulation, *Medical Times and Gazette*, London (1867), I., p. 137; Koestlin, *Ein Fall von Luft im Herzen*, Med. Correspondenz-blatt d. württ. ärztl. Ver. Stuttgart (1857), Vol. XXVIII., pp. 316–321; De Lavacherie, *De l'opportunité de l'extraction des tumeurs du cou non susceptibles de résolution; réflexions sur l'introduction de l'air dans le cœur par des veines ouvertes accidentellement*, Mém. Acad. roy. de méd. de Belge. Bruxelles (1849), II., pp. 305–376; McPharlin, Death from entrance of air into the veins in a case of compound fracture, *Hosp.*

Gazette (N. Y., 1878), III., p. 20; Massart, *Etude nouvelle sur l'entrée de l'air dans les veines, dans les cas de plaie ou d'operation chirurgicale*, Annales Soc. de méd. d'Anvers (1854), Vol. XV., 5, 57, 113; Mercier, Journal des connaiss (Sept. 1836), p. 108; Meyer, F., Case of injury of the vena jugularis interna, entrance of air, sudden collapse, recovery, *Med. Archives*, St. Louis (1869), Vol. III., pp. 408–410; Miner, Tumor in the neck, admission of air into the vein, death, *Buffalo Med. and Sur. Journal* (1864), pp. 336–338; Mirault, Thèse. Paris. (1832); Mott, Entrance of air into facial vein, *Medico-Chir. Trans.* (1830); Piachaud, *Mort par introduction de l'air dans une veine, pendant l'ablation d'une tumeur du sein avec ganglions dans l'aisselle*, Echo méd.; Neuchât (1857), p. 768; Porter, On the entrance of air into the veins as a cause of death, *Journal American Med. Ass.*, Vol. III., No. 20; Rauch, *Lufteintritt in einen verletzen grösseren Halsvenenast und seine Folgen*, Oest. Med. Wochenschr. Wien (1845), pp. 199–201; Roux, Journ. hebdom. (1833), Vol. II., p. 64; Schmid, *Das Eindringen von Luft in eine Vene während einer Operation am Halse*, Corresp. blatt d württ. ärzt. Ver. Stuttgart (1851), Vol. XXI., p. 53; Schweickhart, *Eindringen von Luft in die Venen; Tod durch Gehirnschlag*, Mitth. des badischen ärzt. Ver. Karlsruhe (1852). XI., pp. 69–71; Smith, R. W., Abscess behind the pharynx, entrance of air into veins, *Dublin Quarterly Journal Med. Sciences* (1844), Vol. XXV., p. 497; Tadlock, entrance of air into divided internal jugular vein, ligation, recovery, *Am. Journ. Med. Sciences* (1875), p. 280; Ulrich, *Tod durch Eintritt von Luft in die Venen*, Med. Zeitschrift des Vereins für Heilkunde (1834, November), p. 132; Warren, J. C., two cases of accidents from admission of air into the veins during surgical operations, *Am. Jour. Med. Sciences* (1832), pp. 545–548; Warren, J. M., tumor connected with the sartorius muscle, secondary cancer of breast, operation, entrance of air into the vein, recovery, *Surg. Observations* (Boston, 1867), p. 529; Wattmann, Prager Viertelj (1844), Vol. II., p. 191.

This list is, of course, not complete, nor does it represent all cases of accidental introduction of air during operations, but the names which are quoted ought to be accepted as sufficient guarantee by the most skeptical, that the fear of this accident is not a myth, but a reality, substantiated by many a sad experience.

III. INTRA-VENOUS PRODUCTION OF AIR.

Spontaneous production of air within the blood vessels of recently deceased persons has been repeatedly observed, and to it has been assigned one of the causes of sudden death. That the air thus produced is a direct product from the blood appears to be negatived by the fact that its occurrence has usually been traced in connection with sudden and exhaustive hemorrhages. It is, in fact, in persons who have died from hemorrhage, that air has been found in greatest abundance in the veins. Lieutaud (Hist. Anatomy, Med. Obs. 55) reports the case of a girl who died suddenly in a state of syncope, after having been repeatedly bled, and in whom the cerebral veins and choroid plexus were found impacted with air. M. Rerolle (Thèse de Paris, No. 129, 1832) has published several cases of the kind, where profuse hemorrhage had existed; in one of fatal epistaxis, the heart, arteries and veins contained large quantities of air. Dr. Graves has noticed emphysema of the abdominal parietes in a sufferer from repeated attacks of epistaxis. M. Rerolle conjectures that, in such cases, air is absorbed by the radicles of the pulmonary veins—hence, the air would have no claim to be considered adventitious. (Todd's Cyclopedia of An. and Physiol., Vol. IV., Part I., p. 145).

It is, however, more logical to assume that, inasmuch as in almost all cases the supposed intra-venous origin of air took place consequent upon severe losses of blood; hence, likewise in connection with loss of continuity of the vascular system, that, owing to the sudden loss of intra-vascular pressure the air may have been aspirated through the openings of some of the bleeding vessels.

The quantity of air found in these instances has been so small, that it has been impossible to make a chemical examination to determine its identity with atmospheric air. In cases where air was found in blood, without loss of continuity of the vessels, it is not impossible that the supposed air was not atmospheric air, but a gaseous product liberated from the blood, or generated in the tissues, producing a gas-embolism which interferes with the function of circulation in a similar manner as when the obstruction is caused by atmospheric air.

IV. EFFECT OF THE HEART AND RESPIRATION ON THE VENOUS CIRCULATION.

As the state of the intra-venous blood pressure constitutes the most important elements both in the prevention and causation of aspiration of air into veins, this subject must be briefly alluded to, in order to determine conditions which act as exciting causes. For the most reliable and comprehensive information on this subject we are indebted to Jacobson (Dr. Heinrich Jacobson, *Ueber Blutbewegung in den Venen,* Virchow's Archiv., Vol. XXXVI., p. 80.) The observations were made on sheep. To determine the effect of the heart's action upon the venous circulation, he measured the blood pressure in veins with the manometer. These measurements were made on veins in close proximity to the heart, as the lower portion of the jugular and subclavian, as all attempts to approach nearer the heart seriously impaired the normal physiological conditions of the respiratory and circulatory organs. His measurements gave the following results:

In the left vena anonyma	— 0.1 mm. Hg.
In the right vena jugularis	+ 0.2 " "
In the right vena subclavia	— 0.1 " "
In the left vena jugularis	— 0.1 " "
In the left vena subclavia	— 0.6 " "

The following are his observations on some of the more distal veins in the same animal:

In the external facial	+ 3.0 mm. Hg.
In the internal facial	+ 5.2 " "
In the brachial	+ 4.1 " "
In a branch of the same . . .	+ 9.0 " "
In the crural vein	+ 11.4 " "

The experiments of Ludwig and Mogk, although made in a similar manner, led to more variable and inconstant results; at one time they found the blood pressure in the crural vein 6.8 mm. Hg., while on another occasion, under similar circumstances, it measured in the same vein only 1.9 mm. Hg. Donders refers this want of uniformity to the respiratory movements of the chest, believing that the aspiratory movements of the chest affect the venous circulation more than the *vis a tergo* from the capillary system. Poiseuille claimed that in his experiments the manometer was affected by the respiratory movements of the chest only, when it was inserted into veins in close proximity to the heart, as in the lower portion of the jugular and the external iliac veins, while in more distant veins the column of mercury was not affected by the movements of the chest. Volkmann obtained the following measurements:

In the facial vein of a goat	41	mm. Hg.
In the jugular vein of a goat	18	" "
In the metatarsal vein of a calf	27	" "
In the jugular vein of a calf	21.5	" "
In a subcutaneous vein of the neck of a horse	44	" "
In the jugular vein of the neck of a horse	21.5	" "

Magendie found the blood pressure in the external jugular vein of a dog 18 mm. Hg., and in the crural vein 50 mm. Although the measurements of the intra-venous blood pressure taken by different observers are at great variance, and although their figures are indicative of the opinions held by the different experimenters as to the effect of respiration upon the return of venous blood, yet they all agree in locating the minimum degree of intra-venous pressure in the veins nearest the heart. The effect of respiration on the venous circulation was thoroughly investigated by Magendie. He introduced an elastic tube into the internal jugular vein, and observed that blood would escape only during expiration. The same experiment was made on the crural vein by directing the tube towards the heart, followed by the same result. The suction force exerted during inspiration was sufficient to counterbalance the auricular contractions. In making these experiments, air was frequently drawn into the heart during forcible inspiration. Barry introduced through the jugular vein of a horse a bent tube of glass, one extremity being passed into the right cavity of the heart, or the vena cava, and the other into a vessel containing a colored fluid. He found that with each act of inspiration the liquid rose in the tube, demonstrating the effect of a notable suction force. He found that this suction force was increased by preventing the entrance of air into the chest by the trachea. He was of the opinion that this force from the chest was exerted, not only in the large veins near the heart, but throughout the entire venous system.

Schweinburg (*Die Bedeutung der Zwerchfell contractionen fuer die respirat. Blutschwankungen*, Du Bois-Reymond's Archiv., 1881, p. 475) has studied the effect of respiration on the circulation by producing paralysis of the diaphragm by section of the phrenic nerves. He states, that when diaphragmatic respiration has been artificially arrested, the difference of blood pressure observed during respiration ceases entirely, or nearly so. From this he concludes that the action of the diaphragm causes, to a certain extent, these differences. Even after opening the abdominal cavity, the difference in blood pressure is very slight. As the principal cause in abolishing the effect of respiration upon the circulation, he looks upon the compression of the abdominal vessels during inspiration, causing the increase of blood pressure during inspiration and its diminution during expiration, by diminishing intra-abdominal compression. If the jugular vein in an animal is exposed, direct observations show conclusively that the direct influence of inspiration cannot be felt much beyond these vessels. The flaccidity of the walls of the veins will not permit the extended action of any suction force, but the flow of blood in the distant veins is accelerated by the intermittent emptying of the veins by the respiratory act. Barry and Donders ascribe to the aspiratory function of the chest the principal motor in the return of the venous blood. Donders estimated the aspiratory force of the inspiratory movements of the chest at seven mm. Clinical observation and experimental research have established the fact that the venous circulation is directly influenced by respiration within a certain area, and that aspiration of air, in the majority of cases, takes place in those veins thus affected, thus constituting the justly and much dreaded "danger-zone." Instead of speaking of the effect of respiration on veins as a cause of aspiration of air, some authors speak of the vein-pulse, and limit the danger-zone to such veins as pulsate. Under certain circumstances the pulsations of the arteries are communicated directly to the veins through the capillaries. In such instances it is necessary that the arterioles are relaxed, as has been ascertained by

Bernard in observing the circulation in glands during their physiological activity. If a vein be opened in a gland during its physiological activity, the blood retains partly its arterial hue and escapes in intermittent jets, as from a divided artery. According to recent physiological investigations veins continue to pulsate independently of the arterial system and the cerebro-spinal centres. Luchsinger (*Von den Venenherzen in der Flughaut der Fledermäuse*, Pflueger's Archiv., 1881, Vol. XXVI.) examined the venous pulsations in the wings of bats. Contrary to Schiff's observations, he found it independent of the central nervous system. Division of the brachial plexus and separation of all tissue connections between hand and body, with the exception of the vessels, did not arrest it. If artificial circulation was established in the organ after amputation, rhythmic venous contractions would be seen even twenty hours after death. Intra-venous pressure was found to be of great importance in these experiments; as soon as it was increased the vein began to pulsate. The seat of these rhythmic contractions, Luchsinger placed in the walls of the vessels, or rather in their muscular structures. They are probably regulated by the central nervous system. Slight increase of warmth and electric tetanization accelerate the contractions. High temperature causes diastolic stasis. Nitrite of amyl increases the pulsating only to arrest it later. Schiff has since satisfied himself that these pulsations continue after division of the brachial plexus and ligature of the vessels, and even in the veins in detached pieces of the bat's wing. Brunton (On Pulsations in the Jugulars and other Veins, Med. Press and Circular, July 2, 1879) has made the same observations on man in regard to the effect of increased intra-vascular pressure in producing venous pulsations in the larger veins. He finds that the pulsation of the jugular vein is sometimes confined to one side, the left one. In one of his cases, the jugular on the left side was much more distended than the right jugular, the distension increasing whenever the vein was compressed just above the clavicle. Whenever this compression was repeated in the rhythm of the pulse, the increase and decrease of the blood in the vein assumes the character of pulsation, and for this reason the author has arrived at the conclusion that the venous pulsation in such instances is caused by compression of the vena anonyma by the aorta. All cases of unilateral jugular pulsation observed by Brunton occurred in anæmic women. In one of these the pulsation took place only while the patient was affected by some emotional excitement; in another, only during expiration. In rabbits the author has repeatedly observed rhythmical contractions of the pulmonary veins, the vena cava inferior, and the portal vein, occurring immediately after the death of the animals. These pulsations were present either after complete cessation of the heart's action, and sometimes even before death, and, as the pulsations were more frequent than the heart's action, it was plain that they occurred independently from any contraction of that organ. In consequence of long continued pressure on a vein, the author has seen tonic contractions to take place, especially in smaller veins, and this may explain the cause of some of the irregularities of the circulation and subsequent transudation.

Riegel (*Zur Kenntniss von dem Verhalten des Venensystems unter normalen und pathologischen Verhaeltnissen, Berl. Klin. Wochenschrift*, 1881, No. 18) has made vein pulsation a special subject of investigation, and as the result of his researches he has come to the following conclusions: I. There exists in the normal condition a pulsation of the jugular vein. II. This normal pulsation is always anadicrotic, *i. e.*, its wave rises in two distinct intervals. This anadicrotic wave corresponds, in contradistinction to the pulsation of the carotids, to the diastole of the heart. The short catacrotic line or wave corresponds to the systole; the anacrotic, to the diastole of the heart. Synchronous with the systole the contents of the vein are emptied into the heart, while during the diastole stasis takes place in the veins. King (Guy's Hosp. Repts., 1837, p. 108), in his interesting essay "On the safety-valve function in the Right Ventricle of the Human Heart," demonstrates the existence of venous pulsations in the veins of the hand, the median veins of the forehead, and the external jugular, which he observed after a full meal. The pulsations were made plainly visible by taking a delicate thread of sealing wax about two inches in length, one end of which was fixed across the vein with a little tallow, so as to make a long and excessively light lever, capable of indicating a very slight movement in the vessel. The movements of the lever produced by the vein pulse correspond in frequency with the pulsations of the arteries in the same vicinity, but did not correspond in time, as the venous pulse followed the arterial systole, showing conclusively that it was not due to the impulse of an adjacent artery. The pulsations could only be caused by the arterial wave being continued to the veins through the capillary vessels. In certain pathological conditions, independently of valvular lesion of the heart, he noted a marked increase in the venous pulsation in the dorsal veins of the hand, and other vessels distant from the heart. The subject of the vein pulse affords an interesting topic in physiology, but in connection with this paper it is only mentioned in order to show that the intra-venous tension is only slightly affected by it, and consequently it can exert no direct influence in causing aspiration of air into veins. The venous pulsations, which directly influence the return of the venous blood to the right side of the heart, occur synchronously with the movements of respiration, and are observed only in the veins which are in close proximity to the heart, and in venous channels with firm unyielding walls. The introduction of air can only follow in wounds of vessels where the intravascular pressure is subjected to great variations, either from normal anatomico-physiological conditions or the result of pathological alterations. All causes which prevent a prompt collapse of the walls of a wounded vein must be considered as predisposing causes, while all conditions which tend to produce a vacuum in the wounded vein act as determining causes. The location of the former corresponds to the point of injury, while the latter are always represented by the aspiratory action of the chest during inspiration.

V. ASPIRATION OF AIR INTO THE SUPERIOR LONGITUDINAL SINUS.

Nearly all of the older physiologists were of the opinion that aspiration of air into veins could only take place in vessels which were in close proximity to the heart and within reach of the venous pulse. Mery claimed that the effect of thoracic aspiration on the venous circulation extends to the sinuses of the dura mater and the venous channels of the diplöe of the cranial bones. Bernard was aware that air might enter the sinuses in case these structures were wounded, as this accident occurred a number of times in his experiments on animals where the superior longitudinal sinus was opened for other purposes. He believed that the air, after entering the sinus, reaches the heart through the vertebral veins and the vena azygos. Death, in such instances, took place in eighteen minutes, while forty-five minutes were required if death resulted from hemorrhage alone.

Volkmann's case, reported in another part of this paper, demonstrates to a certainty that death may be caused by the entrance of air through a wound of the longitudinal sinus, and although this is the only authenticated case on record, similar cases have undoubtedly occurred before, but the real cause of death was not recognized, and the fatal result was attributed to some other source. This subject, of aspiration of air into the longitudinal sinus, was made the object of experimental inquiry by Genzmer, one of Volkmann's assistants. (*Exstirpation eines faustgrossen Fungus duræ matris, tödtlich verlaufen durch Lufteintritt in den geöffneten sinus longitudinalis.* Verh.d.deutschen Gesellschaft f. Chirurgie, Vol. VI., p. 32.)

The experiments were made on dogs, as this vessel in rabbits was found too small for the operation. Nine experiments were made. The animals were made partially insensible by morphine injections. The skull was exposed by an incision which was carried from the occipital bone to the forehead; with a small straight chisel a section of bone about six ctm. square was mapped out by cutting through the external table, anteriorly to the prominentia occipitalis externa, and which was completely detached with a hollow chisel. The dura mater having thus been freely exposed, the posterior portion of the longitudinal sinus, which was about two mm. in width, was made accessible about its middle. Between two small hooks the sinus was made tense and divided transversely, carefully guarding against injury to the subarachnoidean space. In some of the experiments the wound was kept patent by making traction on its margins with the hooks; in others this precaution was unnecessary, as the edges of the wound retracted sufficiently to keep it open. For several minutes after incision the bleeding continued profusely; the blood was quite red, and escaped with some degree of force, the pulsations being plainly visible and synchronous with the heart's action. The stream was also perceptibly increased and diminished with the respiratory movements of the chest. After a few minutes had elapsed, the hemorrhage became less profuse. In case the animal died, the heart and lungs were removed, after carefully tying the large vessels so as to prevent the escape of air from the heart. To secure accuracy in ascertaining the presence of air in the heart, this organ was opened under water, when the rising bubbles would indicate its presence. In three cases, in two of them the animal breathed through a tracheal canula, the double rhythm in the blood column was lost soon after the sinus was opened, and the blood continued to flow until the animal died, which was usually the case after 35, 40 and 53 minutes, the stream from the peripheral end of the sinus growing constantly less during this time. In all of these cases the central end of the sinus was completely filled with a thrombus, and no air was found in the heart. In two other cases the double rythm continued until life was extinct, which was the case after twelve and nineteen minutes. After the first two or three minutes, the bleeding diminished, and, by removing the blood from time to time with a sponge, it could be seen how air was aspirated during inspiration through the gaping wound. During forcible expiration, or on compressing the chest, air-bubbles escaped with the blood from the wound from the proximal end of the sinus. As the bleeding diminished, air aspiration became more copious and more frequent. An examination of the cadavers of these animals revealed that the right side of the heart contained air and spumous blood. In the next two cases, artificial dyspnœa was produced; in one instance by dividing both pneumogastric nerves, in the other by closing the tracheal canula through which the animal was breathing. In the first case air entered early, and the animal died in 16 minutes; in the second case air entered freely during the forcible inspiratory efforts; the animal died in 24 minutes. In both these cases air was found in the right side of the heart, and in the subpleural vessels. In the last two experiments the animals were killed 15 and 60 minutes after the sinus was opened, by puncturing the brain with a needle. In the first case a considerable amount of air was found in the right side of the heart; in the second case the amount of air contained in the right side of the heart was less—the apparent difference being due to the presence of a thrombus in the central end of the sinus in the last case, which prevented further ingress of air.

In recapitulation it may be stated, that in six out of nine experiments, air entered the longitudinal sinus, thus proving conclusively that wounds of this great reservoir of venous blood are not only dangerous from the loss of blood, thrombosis and inflammation, but may also become the direct cause of sudden death by admitting air into the venous circulation.

EXPERIMENTS.

These experiments were made by the writer for the purpose of ascertaining more fully the conditions which determine the entrance of air into a wounded longitudinal sinus, and, at the same time, to obtain reliable information concerning the prophylatic measures, as well as to determine the best methods of arresting hemorrhage in wounds of this vessel. All operations were made under antiseptic precautions; when not specified, no anæsthetic was used. The field of operation was cleanly shaved, and the surface thoroughly disinfected with a 5 per cent. solution of carbolic acid; during the operations frequent use was made of the irrigator, using a warm 2 per cent. solution of the same antiseptic. When the animal survived the operation the wound was closed with continued catgut sutures, dressed with iodoform, and a compress of salicylated cotton retained by a roller bandage. The operation consisted in making a longitudinal incision in the median line of the skull, reaching from the external occipital protuberance to near the upper extremity of the frontal sinuses. The soft parts, with the periosteum, were separated and reflected on each side, so as to lay bare the bone over a sufficiently large area for the ready use of the bone-cutting instruments. A medium-sized trephine was applied over the middle of the longitudinal sinus, and a button of bone carefully removed, so as to prevent injury to the underlying vessel. The enlargement of the circular aperture was effected with a hollow chisel and Luer's bone-forceps. The opening in the bone was made of an oval or oblong shape, with the longest diameter parallel to the sinus, in order to bring into view a large extent of the vessel with a minimum destruction of the cranial vault.

Experiment No. 1.—Small skye terrier, weight 12 pounds. Ether used as an anæsthetic. Longitudinal sinus laid bare to the extent of one and a half inches, by an oval opening in the skull. Copious hemorrhage from a vein leading into sinus, which was arrested after ligature. Two catgut ligatures were placed underneath the sinus about one-half inch apart, and the vessel cut transversely between them. The bleeding was very copious, the blood escaping in jets synchronous with the heart's impulse; the flow was also distinctly increased and diminished by the respiratory movements of the chest. During inspiration the stream was diminished, while expiration was always attended by a decided increase in the force of the jet, and the amount of bleeding. No air was seen to enter, although the hemorrhage had been very profuse and continuous for a considerable length of time. As it was intended by this experiment to prove that sudden obliteration of the longitudinal sinus is not incompatible with life, the distal ligature was tied, with the effect of nearly, but not completely, arresting the hemorrhage, as some blood escaped from the proximal end of the vessel. It was now intended that air would be more prone to enter through the gaping wound in the sinus, as the blood pressure from the distal end of the vessel had been arrested by the ligature, but as this accident did not take place after a few minutes, the second ligature was tied, and the wound in the skin united with a continued catgut suture, and the antiseptic compress applied. The animal showed no other symptoms except great prostration from the sudden and profuse loss of blood. After an hour it rallied, and apparently was in full possession of all its special senses, and was able to walk about as usual. The next day it manifested a ravenous appetite, and, during the whole time it was kept under observation, it showed no signs of illness or discomfort. The wound united by primary union, the skull showing the oblong bony defect at the site of the operation, through which the pulsations of the brain could be distinctly seen and felt. Unfortunately, the animal ran away after complete recovery had taken place, and deprived me of the opportunity to study by post-mortem examination the local effect on the intra-cranial circulation by the operation. This experiment tends to prove that ligature of the longitudinal sinus can be performed without seriously compromising the functions of the brain, and that in certain well defined instances this procedure might be resorted to in practice with a view of preventing hemorrhage from, and entrance of air into, this vessel, in intentional and accidental wounds of the sinus.

Experiment No. 2.—Small tan cur; weight 10 pounds. Partial ether anæsthesia. Longitudinal sinus opened by two transverse incisions in close proximity; hemorrhage alarming, at first in jets, and, as the bleeding diminished, in a more continuous flow. At first the blood was bright red, but as respiration became impaired, it grew darker in color. Dilating forceps were introduced into the proximal wound; the hemorrhage continued, but no air entered as long as the animal was in a lying position, but as the respiration became more irregular and superficial, artificial respiration was resorted to, and the head placed in an elevated position, whereupon the heart suddenly ceased to pulsate, and upon applying the ear to the præcordial region, a few irregular and very feeble contractions were heard, attended by a distinct churning sound, when the animal suddenly expired. Before death electricity was used with the effect of improving the respirations, but it had no effect whatever upon the action of the heart. Death took place about three-quarters of an hour after the sinus was opened. At the examination, immediately after death, all the tissues and organs were found in an exsanguinated condition. All the vessels leading to and from the heart were carefully tied, and the organ removed. On being placed in water it floated like a cork; the right auricle and ventricle were dilated, and on being opened under water, bubbles of air and only a very slight amount of spumous blood escaped. The pulmonary artery was also distended with air. The left ventricle was almost completely empty. In this instance the animal almost bled to death from the wounds in the longitudinal sinus, and yet no air entered, although the wound was kept patent with a pair of forceps. The entrance of air was caused by the elevation of the head and the forcible movements of the chest during the performance of artificial respiration. To judge from the amount of air found in the right side of the heart and its effects, the air must have entered quickly, and in considerable quantity, distending at once the right side of the heart in the diastole, after a few feeble attempts to force it from the right chambers. I believe, if the animal had been left in the lying position, and the head dependent, that death would have taken place from hemorrhage, as the blood which was draining through the sinus prevented the entrance of air, but as soon as the head was raised, the contents of the sinus by gravitation flowed towards the heart, and air entered with it to fill the vacuum which was being prepared by the diminished blood supply to the brain, and the acceleration of venous return, as well as the increased aspiration of the chest, which was brought about by the attempts at artificial respiration.

Experiment No. 3.—Horse about twelve years old. Partial chloroform anæsthesia. Animal kept lying on the ground, head even with the body. Longitudinal sinus exposed for about two inches and incised longitudinally one inch. Hemorrhage very profuse; blood at first bright red, gradually growing darker in color; double waves well marked. After about three quarts of blood had been lost, and the hemorrhage still continuing at the same rate, and not being readily controlled by the ordinary compression, it was decided to implant an aseptic sponge into the sinus. This was done, and the external wound united over it by the continuous suture. No air was seen to enter the wound, and auscultation over the heart revealed no abnormal sounds. During the operation of chiseling, the apices of the frontal sinuses were opened, which led to the fear that infection of the wound would subsequently take place from this source. This expectation was realized. The animal rallied soon after the operation, and appeared to be quite well for three days subsequently, grazing in the pasture with other horses. On the morning of the fourth day it was found dead. Examination of the cadaver showed that the proximal end of the sinus was closed by a thrombus firmly adherent to the walls of the vessels and the implanted sponge, but about the distal end of the sponge, at a point which corresponded to the opening in the frontal sinuses, the brain and meninges showed all the appearances of acute septic inflammation. If infection had not taken place, the aseptic sponge would have fulfilled all the purposes for which it was intended—arrest of hemorrhage and obliteration of the sinus. It seems to me that in cases of uncontrollable hemorrhage from accessible sinuses, the implantation of an aseptic sponge would prove a safe and efficient measure against hemorrhage, and would offer no obstacle against obtaining primary union and definite closure of the vessel, as during the process of granulation the sponge disappears by absorption.

Experiment No. 4.—Horse 14 years old, in good condition. This experiment was made for the purpose of confirming the suspicions already gained that the force of gravitation constitutes the most important factor in determining the admission of air into an open sinus of the dura mater; consequently no anæsthetic was given, but the animal was firmly held by a bit, and the operation was performed without any difficulty while the animal was in a standing position with the head elevated. With the trephine and chisel an oval opening of about two and one-half inches in extent was made over the longitudinal sinus. After all oozing had ceased, and the sinus being fully in view, its anterior wall was divided completely in a transverse direction. The edges of the wound immediately retracted, forming a diamond-shaped opening, through which blood escaped in moderate force, but not nearly as copiously as on previous occasions, when the animals were in the lying position. During the first inspiration after incision, air entered with a loud gurgling or lapping sound, and on applying the ear over the apex of the heart, a loud churning sound was heard synchronous with the movements of the heart. During expiration air-bubbles were seen to escape from the proximal end of the sinus. As soon as the head was lowered the hemorrhage greatly increased, but air never entered in this position; but as soon as the head was elevated, hemorrhage either ceased entirely, or was at least greatly diminished, but air was sure to enter during inspiration. These manœuvres were repeated a number of times, and always with the same results. As the amount of air which was aspirated increased, the respirations became more labored, and signs of cyanosis became apparent. An attempt was made to close the wound in the sinus by sutures, and in this way arrest the hemorrhage. Three cat-gut sutures were passed through both edges of the wound, but on attempting to approximate its margins, every one of them tore through the tissues before the parts were in apposition, proving conclusively that transverse wounds of the longitudinal sinus cannot be sutured, owing to the unyielding nature of the tissues. The external wound was completely closed by the continuous suture, and a firm, graduated antiseptic compress controlled the bleeding. During the whole time of the operation, which lasted over an hour, some one of the bystanders listened to the heart's action, and the loud splashing or churning sounds were constantly heard. When the animal was released it commenced grazing in the pasture, and appeared as well as before the operation. The heart was examined at intervals of thirty minutes, and the abnormal sounds grew more feeble, and after an hour had entirely disappeared. The sound produced by the entering air, I have described as lapping, resembling very much the sound produced by the lapping of a dog or cat; the best possible word for this sound is the German expression, "schluerfend." When air enters through a wound of the longitudinal sinus this sound is characteristic, and is always the same, and, in case the animal operated upon is a horse, it is sufficiently loud to be heard at some distance. Experiments have shown that horses are most tolerant to the presence of air in veins, on account of the unusual development of the right ventricle, which has sufficient power to force the air through the pulmonary circulation, and this experiment would certainly tend to corroborate this observation, as air in large quantities was aspirated at least a dozen times during the operation, and that most of it entered the right side of the heart and was not returned, is evident, from the persistence of the sounds due to the presence of air for a period of two hours, and yet, aside from a certain degree of embarrassment of respiration, the animal suffered no inconvenience. The wound healed by primary union. The defect in the skull remained permanent. The animal was killed about four weeks afterwards. Postmortem appearances: The trephine opening filled with cicatricial tissue.

Proximal end of sinus just behind trephine opening contains one large granulation thrombus. Cicatricial tissue filling almost the entire lumen of the sinus. Anteriorly the sinus is somewhat contracted and smooth; no thrombus here, or evidences of proliferation. The circulation is apparently restored by the formation of a new channel, or dilatation of a pre-existing one. This new sinus is located to the left of the median line. The lateral sinuses are very much enlarged.

Experiment No. 5.—Young yellow dog, weight about 15 pounds. Partial ether anæsthesia. Longitudinal sinus exposed and transversely incised at two points in close proximity. Hemorrhage profuse; was allowed to continue for over half an hour, in order to estimate the length of time which would be necessary for death to occur from this cause uncomplicated by admission of air. When the animal appeared moribund, both ends of the sinus were ligated. The heart's action was very feeble and irregular. Death occurred in 35 minutes. At the examination after death, no air was found in the vessels or heart, and death was plainly attributable, in the absence of any other cause, solely to the loss of blood.

Experiment No. 6.—Newfoundland dog; weight 50 pounds. Partial ether narcosis. During the removal of bone over the sinus severe hemorrhage was encountered from the large venous channels in the diplöe. The great irregularity of the external surface of the skull led to a mistake, as the frontal sinuses were again opened. The longitudinal sinus was laid open by an incision half an inch in length, in a parallel direction to the vessel. Hemorrhage very profuse for half an hour, checked at times by compression, when it finally diminished, and the wound was closed. After the operation the animal walked with a staggering gait, and would run against objects indiscriminately, showing that sight was greatly impaired, inasmuch as the animal had fully recovered from the effects of the ether. No air was seen or heard to enter the sinus. Heart sounds feeble, but otherwise normal. Death in this case took place a week after the operation, from lepto-meningitis. The source of infection undoubtedly was again traceable to injury of the frontal sinus, as the earliest evidences of the disease were found nearest to the opening in this structure.

Experiment No. 7.—Old decrepit horse. Operation was performed while the animal was in the erect position. On removing disc with trephine, a longitudinal wound, one-half inch in length, was found in the anterior wall of the sinus, through which bright red blood escaped. Double pulsation well marked. Almost immediately after the removal of the disc of bone, and before more than an ounce of blood escaped, air entered with a loud and distinct lapping sound, audible to all who were present. On applying the ear over the heart, the same loud churning sounds were heard. As the head was lowered, the flow of blood became more forcible and copious, but no air entered. As soon, however, as the head was elevated, bleeding diminished, and air entered during almost every inspiration. Respiration became labored, and after air had entered four or five times in succession, the animal fell to the ground. In this position no further entrance of air occurred, but the hemorrhage continued copiously, the blood flowing in a continuous stream, with a well marked double jet, synchronous with the action of the heart, and the respiratory movements of the chest. The opening in the skull was enlarged to two inches in length and one and one-half inches in width, so as to expose the sinus freely. A number of catgut sutures were now introduced through both lips of the wound, and, on attempting to tie them, great difficulty was experienced in approximating its margins, which could be brought nearly, but not completely, in contact without the sutures tearing through. The tying of all the sutures resulted in diminishing, but not arresting the bleeding, showing conclusively that in longitudinal wounds of the sinus suturing is an imperfect and unreliable measure in arresting hemorrhage, to say nothing of the difficulty which is experienced in passing the sutures at such great depths and in the limited space furnished by the artificial opening in the skull. The wound was not closed, but tamponed with iodoform cotton, in order to observe from time to time the processes which nature would initiate in the restoration of the wounded sinus. Half an hour after the first entrance of air, the churning sounds in the heart had much diminished, and they almost completely disappeared after the lapse of one hour. The animal recovered completely from the immediate effects of the air-embolism, the respiration having again become normal in frequency and character. After two hours the tampon was removed, but bleeding again occurred, and it was replaced. The animal died 24 hours after the operation, probably from the combined effects of the loss of blood, hemorrhage into the subdural spaces, air-embolism and senile marasmus. At the examination of the cadaver, a subdural clot was found on the right side of the brain, which weighed about half an ounce; on the left side of the sinus, a second but smaller subdural clot was found. Trephine opening filled by a coagulum. One of the sutures had lost its hold by tearing through the tissues of one margin of the wound. Within the sinus a small fragile clot was found, also a small wound in the lateral wall of the sinus, which served as the source of hemorrhage into the subdural space. This experiment illustrates well the danger of plugging the opening in the skull for the purpose of arresting hemorrhage in case the lateral walls of the sinus are injured, as it will almost necessarily lead to subdural hemorrhage, and expose the patient to all the disastrous consequences incident to this occurrence. In this instance sponge implantation would not only have more successfully guarded against external bleeding, but also would have served as a sure prophylactic against extravasation into the subdural space. It also teaches that suturing, in cases of wounds of the longitudinal sinus, with limited defects in the bony walls of the cranium, is impracticable, unreliable and unsafe, and should never be resorted to, unless the dura mater is so extensively exposed or separated as to permit, by making gentle traction, perfect and complete approximation of the margins of the wound.

VII. PRACTICAL SUGGESTIONS.

In order to study the conditions which favor the aspiration of air into a wounded sinus of the brain, it is necessary to call attention to some of the peculiarities of the intra-cranial circulation. Mosso (*Ueber den Kreislauf des Blutes im menschlichen Gehirn*, 1881), who has made this a special subject of investigation, asserts that the intra-vascular pressure in the veins within the cranium is higher than in the veins of any other part of the body. Actual measurements have shown that the blood pressure in the longitudinal sinus is equal to 100-110 mm. Hg. The probable cause of this phenomenon is, that the force of distension of the arteries within the closed and unyielding cranial cavity is added to the *vis a tergo*. The intra-cranial veins show distinct pulsations, which are dependent upon the pulsations of the arteries, and their movements are so plain that they can be graphically demonstrated; every diastolic movement in the artery corresponds to a venous pulse. During the pulsations of the brain, Mosso claims, with Donders and Berlin, that the cerebro-spinal fluid does not escape into the spinal canal. In a case of spina bifida, he has been able to trace respiratory, but no circulatory movements. When the tumor was compressed, only a very slight increase in the volume of the brain could be detected at the fontanelle, even if nearly the whole contents of the tumor were pressed into the spinal canal. G. Burkhart (*London Lancet*, October 15, 1881) has published the results of his observations on the movements of the brain, which he made on four patients who had suffered partial loss of the cranial vault. The tracings obtained represented three forms of movements,—pulsatile, respiratory and vascular. The cerebral pulsation has the form of a tricrotic or tetracrotic pulse, the phases following one another in about the same time as those of the carotid pulse. His observations led him to the conclusion that the brain presents the same movements within the intact skull, as in the infant, or when a defect in the skull exists, the result of traumatism. The brain expansion is synchronous with the dilatation of the vessels, and takes place in the direction of the vascular ramifications. The resistance is in inverse proportion to this expansion. In the closed skull the excess of pressure in the arteries aids materially the propulsion of the blood through the veins, and also that of the sero-lymphatic fluid. In the open skull the curve rises during expiration and falls during inspiration. All actions which increase the respiratory movements, increase the height of the curve. A secondary elevation follows labored inspiratory movements, but the pulse waves are never completely effaced. The vascular curves occur independently of respiration or pulsation. The height of the curves bears no constant relation to their length. They are notably influenced by psychical influences. They are produced by movements of the vessels by means of the vaso-motor nerves, and can be made very conspicuous by irritation of the cervical sympathetic. Bergmann (Verhandlungen d. deutschen Gesellschaft f. Chirurgie, Vol. X., p. 14), in his remarks on the movements of the brain (in opposition to Mosso), at the meeting of the Congress of German Surgeons, in 1881, insists that the cerebro-spinal fluid acts as a regulator in maintaining the equilibrium between the arterial and venous circulation within the cranium. The pulsations of the sinuses of the dura mater were discovered and studied under his supervision at Dorpat as early as 1873. He argues that these pulsations are very slight, and on that account, insufficient to counterbalance the arterial pulsations. He explains the pulsations of the sinuses in the same way as Donders and Jacobi have accounted for the pulsations in the veins of the papilla of the optic nerve. The pulsations are the result of increased tension in the cerebro-spinal fluid during the arterial systole and the consecutive diminution of intra-cranial pressure during the arterial diastole. The cranium being a closed cavity, with unyielding walls, it is not difficult to understand that in case one of the sinuses is opened by a wound which communicates with the atmospheric air, the sudden loss of blood will have a tendency to create a vacuum which is filled by the admission of air which reached the left side of the heart with the venous blood.

All circumstances which diminish intra-vascular and intra-cranial pressure must of necessity favor the occurrence of aspiration of air into a wounded sinus. It is evident that aspiration of air into an open wound of the longitudinal or any other sinus of the dura mater, is favored by the following conditions: 1. The force of gravitation. 2. The inspiratory movements of the chest. 3. The condition of the arterial circulation. In considering the prophylactic treatment against the admission of air during operations which involve any of the cerebral sinuses, it is of the greatest importance to keep the head at a level with the heart, to insure regular respiration, and to guard against undue or forcible inspiration, and, finally, to maintain the normal activity of the ventricular contractions. The direct preventive measures consists in :

1. Continuous irrigation of the field of operation.
2. Prophylactic ligation of the sinus.

In resorting to constant irrigation, the fluid used should be an aseptic solution at the temperature of the body, which, if it should enter the venous circulation to fill an empty space, would do no harm either as a toxic agent or by causing coagulation of the blood. A solution of salicylic acid in distilled water, or borated water would be best adapted for this purpose. In extirpating tumors of the dura mater in the region of the longitudinal sinus, where wounding of this structure becomes a necessity, it would not only be prudent, but good practice, to ligate the sinus on each side before attempting the removal of the tumor, as this precaution would surely and effectually prevent the two most dangerous and alarming accidents,—hemorrhage and aspiration of air. This plan was followed by Kuester in removing a sarcoma of the dura mater, in 1881. (Berl. Klin. Wochenschrift, 1881, p. 673.) Experiments on animals and the cadaver have convinced me that this operation can be performed with comparative ease, if the defect in the skull is sufficient in extent to permit the necessary manipulations, and, in the event this operation be done for the purpose of facilitating the removal of tumors of the dura mater, this precaution should never be neglected. With a tenaculum the dura mater is seized and drawn forward at the outer border of the longitudinal sinus, and a small incision parallel with the border of the sinus should be made with a tenotome, the incision being only sufficiently deep to divide the dura mater. After making such incisions on each side of the sinus directly opposite each other, the sinus should be grasped with a sharp-toothed spring forceps and drawn forward, when a small, curved, sharp-pointed aneurism needle is passed into one of the openings, and, after penetrating the falx cerebri underneath the vessel, is brought out through the opening on the opposite side. When both of the ligatures are in place, the peripheral ligature is tied first, and after emptying the intervening part of the vessel of its contents, the proximal ligature is also tied. If both of the ligatures have been properly applied, the intervening portion of the sinus can be opened or excised with the tumor without risk of hemorrhage, or the introduction of air; at the same time it will greatly facilitate thoroughness in the removal of diseased tissue. I am firmly convinced that the preliminary ligation of the longitudinal sinus will become an established procedure in all cases where tumors of the dura mater are so situated that their removal implicates this structure, and that it will render possible the removal of tumors which, without it, would place in great and immediate jeopardy the life of the patient by hemorrhage or the admission of air. The process of circulation in the sinus is the same as in the veins, and is accomplished in the same brief period of time. In accidental wounds of the sinus, ligation should be resorted to whenever the original defect in the skull is sufficient to permit the necessary manipulations, or when simpler methods have failed to accomplish the same object. Implantation of an aseptic sponge into a wounded sinus should be resorted to in all cases of wounds of the lateral walls of the sinus in cases of accidental wounds where ligation is impossible and where other measures have failed to arrest the hemorrhage. The sponge should be large enough to make gentle pressure upon the inner surfaces of the sinus, and yet sufficiently firm to arrest the circulation in the vessel, so as to prevent the escape of blood into the subdural space. The hæmostatic action of the aseptic tampon is made more efficient by adding external compression, applied in the form of a graduated aseptic tampon. If the wound remains aseptic, the sponge forms a nucleus for the thrombus, and is infiltrated by connective tissue cells from the intima and adjacent tissues, and is gradually removed by absorption as the definitive obliteration of the vessel proceeds. Small wounds of the sinus can be readily and safely closed with the lateral ligature applied in the same manner as in similar wounds of the veins.

In recapitulation, we are warranted in stating the following conclusions:

1. Elevation of the head is the direct and most essential cause in the production of air embolism through a wound of the superior longitudinal sinus.

2. Suturing of a wound of the superior longitudinal sinus as a hæmostatic procedure is unreliable, and in most instances anatomically impossible.

3. Prophylactic ligation of the superior longitudinal sinus should be resorted to in all cases where this vessel is involved in extirpating tumors of the dura mater.

4. Implantation of an aseptic sponge into a wounded longitudinal sinus will arrest hemorrhage without interfering with the definitive obliteration of the vessel, and deserves a trial in cases where the lateral walls of the sinus have suffered injury, and where ligation is impracticable.

[To be Continued.]